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LONG TERM STABILITY OF FERMILAB ENERGY SAVER MAGNETS

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Summary

The quench and field properties of Energy Saver dipole and quadrupole magnets are measured at the Fermilab Magnet Test Facility shortly after the magnets have been produced. It is important that magnet properties remain unchanged with time. This question has been investigated by remeasuring magnets at a later time and comparing the two sets of measurements.

Three sets of unbiased data are available:

1) Fifteen dipole magnets were remeasured after they were removed from the "B12" cryoloop test location.[1] At B12, they were subjected to repeated thermal cycles, quenches at high current, steady state operation at high current, and ramping to high current with an accelerator type ramp cycle. The average time between the original measurement and the remeasurement was 22 months.

2) Five standard length (66 inch) quadrupole magnets were remeasured after an elapsed time averaging 5 months. These magnets were in storage during the period between the two sets of measurements.

3) Six long (99 inch) quadrupole magnets were remeasured after an average time of 12 days. These were also in storage.

The remeasurements agree well with the original measurements. The measurement techniques and magnet properties obtained from the full magnet samples are described elsewhere.[2-6]

Dipole Magnets

Quench Results

The results of the Quench Test (quench on rising ramp) and the Cycle Test (quench on flattop for an accelerator type ramp cycle) are shown in Figures 1a and 1b. Table 1 gives the average and spread of the changes. The data were taken at a temperature of 4.61 to 4.69K and have not been corrected for temperature variation.

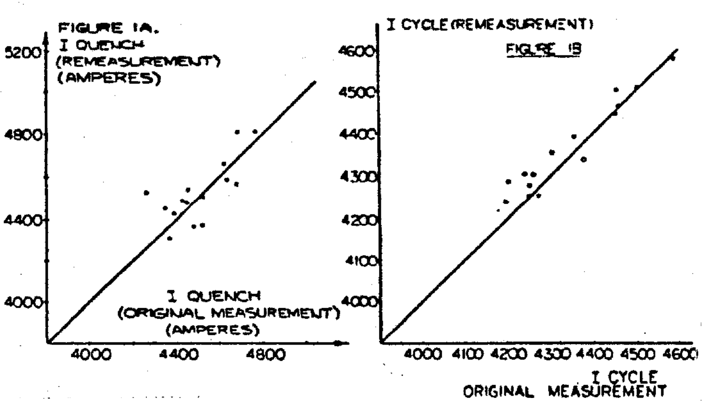


Table 1. Change in Quench and Cycle results

	Average change (amp)	Sigma (amp)
Quench	+18	107
Cycle	+22	34

*Operated by University Research Association, Inc. under contract with the U. S. Department of Energy.

The Quench Test is the only standard measurement which uses an A/D converter instead of a DVM for current measurement. This was done to ensure that the time response would be rapid enough to permit a study of the development of quench signals. Unfortunately, the AM 502 differential amplifier which precedes the A/D converter has a gain accuracy of only 2%; this accounts for most, if not all, of the difference in spreads of the Quench Test and Cycle Test.

Harmonics

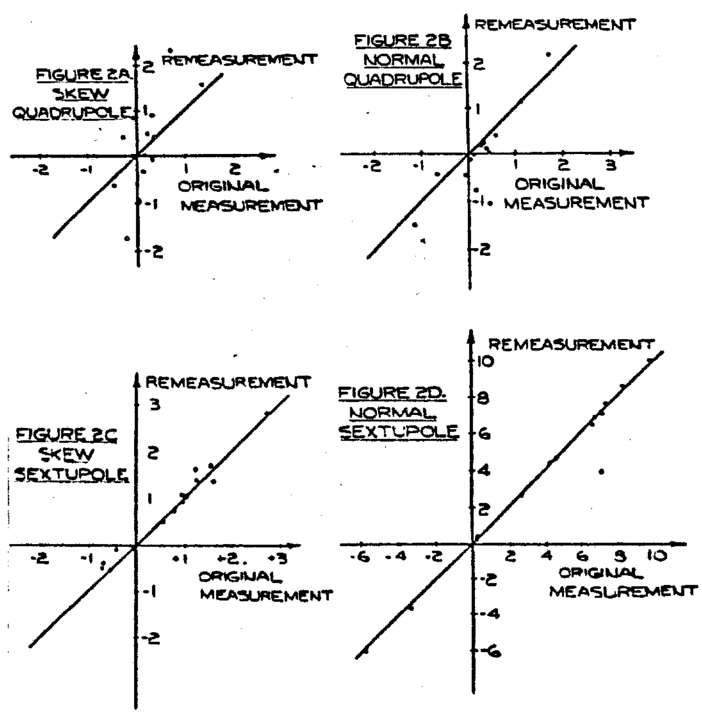
The harmonic content of the field is described using a standard multipole expansion about the center:

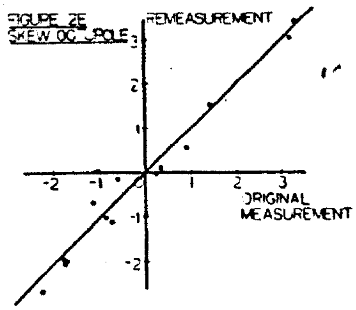
$$B_y + iB_x = B_o \sum_{n=o} (b_n + ia_n) r^n e^{in\phi}$$

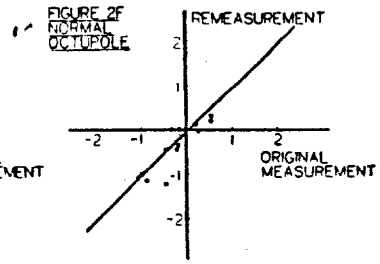
where a right handed coordinate system is used, the proton beam is in the +z direction, the dipole field is in the +y direction, and ϕ is measured from the +x axis with a sense such that the +y axis is at $\phi = +\pi/2$. The a_n and b_n are skew and normal multipole coefficients, respectively, where the pole number is 2(n+1). We have adopted the convention that 1 "standard unit" of a_n or b_n is $10^{-4}(\mathrm{inch})^{-n}$ which gives a convenient scale for presentation of the data.

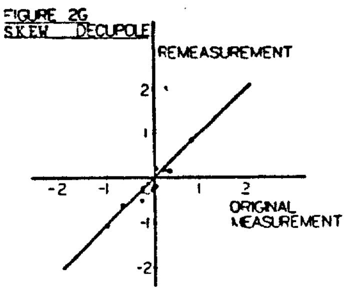
Figures 2a - 2h show the remeasurements versus the original measurements for the lowest eight harmonic coefficients. Figure 3 shows the normal 18 pole for the two sets of measurements. The normal 18 pole is relatively insensitive to magnet construction and coil motion so its stability provides a check that the measurements are correct. The average and spread in the change of coefficients are given in Table 2. One magnet for which the original harmonic measurements were not available has been omitted from the sample.

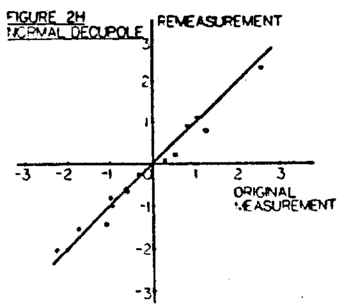
Figure 2. Harmonic coefficients at 4000 amperes











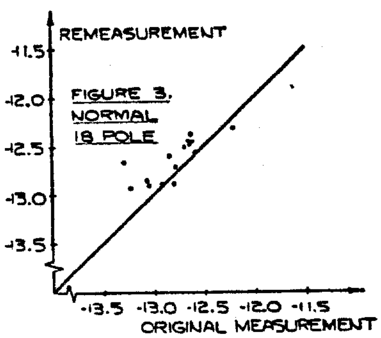


Table 2. Change in harmonic coefficients at 4000 amperes (standard units)

	Average change	Sigma
a_1	+0.31	0.80
b_1	−0.14	0.53
a_2	+0.11	0.18
b_2	−0.14	0.78
a_3	−0.04	0.29
b_3	−0.11	0.24
a_4	−0.06	0.13
b_4	−0.04	0.22
b_8	+0.18	0.17

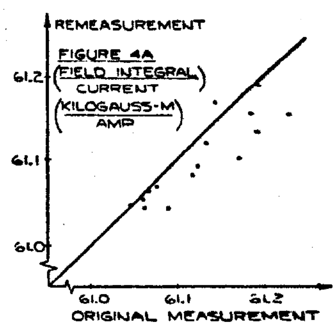
The two sets of measurements agree well with one exception: one magnet shows a decrease in b_2 of 2.8 units. No fault can be found in the data for this magnet. If this magnet is omitted from the b_2 distribution, the average change in b_2 becomes +0.06 and the sigma becomes 0.16. Then the averages and sigmas of the changes are within the absolute measurement accuracy of about 0.3 unit except for a_1 and b_1. These two coefficients show small changes but remain well within the design window of $\pm$ 2.5 units.

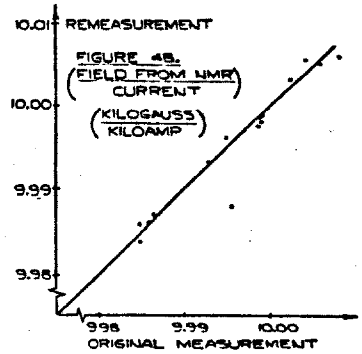
Field Integral

The field integral is obtained directly using stretched wire techniques. The measurement depends on shunt calibrations which have been maintained by comparing NMR measurements of remeasured magnets not included in this sample. It also depends on reliably knowing the stretched wire loop width which was not measured for every magnet but which was studied extensively during two time periods. These studies indicate that the magnet effective length is independent of magnet number. This information has been used to correct for changes in loop width during periods when it was not routinely measured.

NMR measurements were made over most of the magnet length. These are proportional to the field integral if the magnet effective length remains unchanged.

The data are shown in Figures 4a and 4b. The remeasurements show a decrease in average field integral of 3.9 parts in 10^4 and in NMR transfer function (= field / current) of 3.9 parts in 10^5 with sigmas for the changes of 4.6 parts in 10^4 and 2.3 parts in 10^4, respectively. The data shown were taken at 2000 amperes. The NMR measurement is inherently more accurate and avoids the uncertainty in loop width corrections. Limits on changes set by either technique are acceptable.





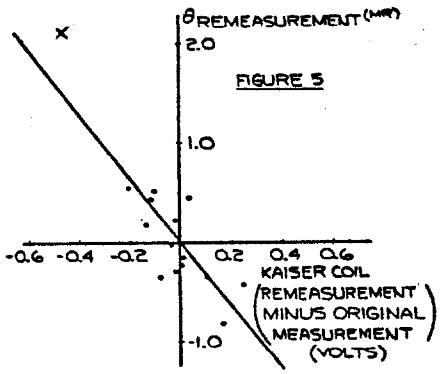
Field Angle

The field angle is determined by measuring the component of the field passing through a stretched wire loop oriented in the vertical plane. Knowing the field integral permits one to calculate the field angle with respect to vertical. This angle is encoded in magnet reference "lugs" which can be used to mount the magnet with a known field direction at a later time. The remeasurements were made with the lugs in a horizontal plane, in which case one expects to obtain a field angle of zero.

A single turn "Kaiser coil" embedded in the magnet yoke laminations provides an independent monitor of field angle changes with respect to the outer magnet iron. Figure 5 shows the remeasured field angle versus the change in Kaiser coil signal at a magnet current of 2000 amperes. The line is the Kaiser coil calibration obtained from other magnets. The change in field angle has an average of −0.02 milliradians and a sigma of 0.42 milliradians. One of the magnets (shown as x in

Figure 5) is known to have had a defective anchor support and is not included in the average or sigma. This defect was the result of an early procedure which affected five magnets, all of which are well identified.

The field angle stability is significantly better than the 1.0 milliradian stability sought.

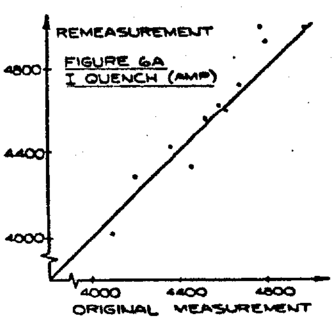


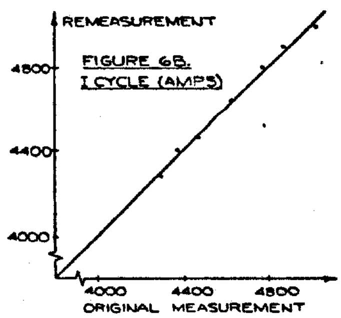
Quadrupole Magnets

The data for 66 inch and 99 inch quadrupoles agree well and have been combined for all measurements except field angle to give a larger statistical sample.

Quench Results

The Quench Test and Cycle Test currents increased by 21 and 8 amperes, respectively, with sigmas for the distributions of 93 and 28 amperes. These results agree well with those obtained for dipoles. The data are shown in Figures 6a and 6b.





Harmonics

Harmonics are expressed using the same conventions as for dipoles except that for quadrupole magnets b_1 is defined to be 1.0 and B_o is adjusted to give the correct quadrupole field. Remeasured harmonics are available on eight of the magnets. Table 3 shows the change in the lowest 8 coefficients. No significant changes have occurred between the two sets of measurements.

Table 3. Changes in harmonic coefficients at 2000 amperes (standard units)

	Average change	Sigma
a_2	+0.35	0.76
b_2	−0.22	0.55
a_3	+0.09	0.40
b_3	+0.11	0.41
a_4	−0.07	0.37
b_4	0.00	0.18
a_5	−0.06	0.49
b_5	+0.12	0.40

Integral Field

The integrated field gradient is measured using four wire stretched wire techniques. At 2000 amperes, the average integrated field decreased by 0.036% with a sigma for the change of 0.101%. The change and sigma are consistent with the 0.1% measurement accuracy.

Field Angle

The field angle is expected to be zero upon remeasurement for magnets levelled from lugs set after a previous measurement. The only unbiased sample available consists of the five standard length quadrupoles. At 4000 amperes, these had a mean field angle of +0.10 milliradians and a sigma of the distribution of 0.57 milliradians upon remeasurement.

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